TABLE 2.—*Fires in the national forests in California showing number and percentage caused by lightning during 1912–1915.*

[Statistics by U. S. Forest Service.]

Forest. [Cf. Fig. 1.]	1912			1913			1914			1915		
	Total number of fires.	Lightning fires.		Total number of fires.	Lightning fires.		Total number of fires.	Lightning fires.		Total number of fires.	Lightning fires.	
	No.	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*	*No.*	*No.*	*P. ct.*
Angeles	72	2	3	130	27	21	136	4	3	116	7	6
California	20	5	25	76	35	46	48	6	12	24	1	4
Cleveland	41	0	0	72	43	60	78	14	18	37	1	3
Eldorado	22	2	9	74	10	14	46	15	33	74	5	7
Inyo	3	1	33	5	3	60	4	3	75	3	0	0
Klamath	85	32	38	126	85	67	163	103	64	219	37	17
Lassen	65	40	62	77	48	62	95	60	63	92	34	37
Modoc	26	22	85	49	36	73	51	35	69	72	52	72
Mono	4	2	50	6	6	100	5	1	20	15	5	33
Monterey	5	0	0	8	0	0	2	0	0	15	2	13
Plumas	96	30	31	156	84	54	149	32	22	108	27	25
Santa Barbara	50	0	0	63	5	8	57	3	5	147	0	0
Sequoia	80	3	4	127	91	72	81	47	58	36	10	28
Shasta	56	29	52	129	62	48	133	34	26	196	77	39
Sierra	67	1	1	172	77	45	88	30	34	37	4	11
Stanislaus	23	3	13	101	49	48	58	12	21	30	4	13
Tahoe	60	5	8	120	45	38	223	53	24	163	17	10
Trinity	37	29	78	137	98	72	53	28	53	143	27	19
Total	812	206	25	1,628	804	49	1,468	480	33	1,527	310	20

Total number of fires during 4-year period	5,435
Number of lightning fires during same period	1,800
Average annual number of lightning fires	450
Percentage of lightning fires to total number	33

It should be borne in mind that all forest fires started as small fires. When lightning strikes a tree it may ignite the tree or the débris and undergrowth beneath, the fire later spreading if conditions are favorable. Of the three kinds of fires recognized by the Forest Service, all may be caused by lightning. These three kinds are (1) ground fires, which smolder indefinitely in the ground, consuming humus, duff, and roots of trees; (2) surface fires, which spread over the surface of the forest floor, fed by undergrowth and débris; and (3) crown fires, which consume the entire forest cover.

As in other States, California has zones peculiarly susceptible to lightning; zones which are perhaps independent of possible topographic influences. Every ranger and lookout recognizes certain well-defined belts where lightning strikes most frequently. As a result, many local traditions have arisen and most of these are based on accurate observations.

According to Mr. Plummer[5] scars traceable in the annual rings of the famous Big Trees of California suggest that great forest fires occurred about the years 245, 1441, 1580, and 1797 A. D. It is known that the American Indians have occasionally set fire to forests in order to clear the land for agriculture, to drive game, or to impede the progress of an enemy, but it is more likely that these great fires were kindled by lightning. These trees also refute the popular superstition that lightning never strikes twice in the same place. Certain trees are known to have been struck eight times, with no other apparent effect than a dwarfed growth.

CONCLUSION.

The importance of lightning as a cause of forest fires may be judged from the foregoing statements. Being of natural origin, lightning is one of the factors which can never be eliminated. However, the situation is not hopeless. The main hope lies in the anticipation of fires and the making available of facilities to subdue them when they occur. The fire-weather warning service gives hope of reward. Thunderstorms with their destructive lightning form simply one of the elements which must be considered. In this, as in other branches, the dominant need is for more field work in order to secure more complete data with reference to each individual forest. As this information is secured further advance may be expected of meteorology in general, and of fire-weather forecasting in particular.

[5] *Plummer, Fred G.* Forest fires. Washington, 1912. (Forest Service Bulletin 117.)

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THE DENSITY OF SNOW.

By Prof. ALFRED J. HENRY.

WITH A NOTE ON THE DISAPPEARANCE AND SETTLING OF SNOW IN 1915–16 NEAR RENO, NEV.

By HENRY F. ALCIATORE, Meteorologist.

CONTENTS.

Definitions.—The generic term density is defined as *mass divided by volume*, or mass per unit volume. The literature of the density of snow frequently contains such terms as "relative" density, "specific" density, and "specific gravity," all of which are comprehended in the simple term density. Relative density as ordinarily defined is the ratio of the mass of any volume of the substance to an equal volume of a standard substance. Water at a specified temperature and pressure is generally taken as the standard substance for solids and liquids and hydrogen for gases. The "specific" density of a substance is merely another way of expressing the specific gravity of the substance. The terms "specific density" and "specific gravity" are interchangeable.

In this paper the term "density" is considered as equivalent to either "relative" density, "specific" density, or "specific gravity" of snow, and it will be expressed numerically as a three-place decimal. Thus, 0.100 (read one hundred thousandths,) that is, snow having a density of 1 to 10, or water equivalent of 1 inch in 10. By disposing of the third decimal, the density values may be thought of as percentages.

The rule followed by the Weather Bureau in disposing of decimals is to increase the last significant figure by

FIG. 5.—Another view of Mount Shasta showing forests about its base, with a sawmill and lumber piles in the foreground. These forests are particularly susceptible to fires from lightning.

unity when the decimal is greater than 5 and to disregard all decimals less than 5. When the decimal to be dropped is 5 exactly, the preceding figure, when odd, will be increased by 1, and when even will remain unchanged.

THE LITERATURE OF SNOW DENSITY.

The greater part of the literature on the subject is in foreign publications; a selected bibilography of papers consulted is presented at the end of this paper.

The subject "snow density", in a broad sense, has developed unevenly, and indeed I may say that it is yet in a state of development. The part taken by the Signal Service and its successor, the Weather Bureau, is outlined in the next paragraph. From this it will be seen that the great, and practically the only, desideratum in the beginning was to determine the quantity of water precipitated as snow. The density of the snow did not seem to be important.

The credit of having pointed out the relation of a snow cover to subsequent weather is due to the late Russian meteorologist, Voeĭkov (Woeikof), more than to any other single person. He first drew attention to the subject in 1871, and his second communication was followed nearly 20 years later by another much greater work, "The Influence of a Snow Cover on Soil, Climate, and Weather" (No. 5 in the list of references at the end of this paper). Preceding the date of publication of the last-named work, the meteorologists of India were engaged in a correlation of the snowfall of the Himalaya, with the subsequent rainfall of the upper Provinces of India.

THE MEASUREMENT OF SNOW IN THE UNITED STATES.

Historical.

Smithsonian Institution.—Systematic meteorological observations in the United States, including the measurement of precipitation in the form of snow, under the direction of the Smithsonian Institution, began about 1848.[1] Smithsonian observers were instructed to use a snowgage and to melt the catch of snow and record the amount of melted snow as rain. Explicit directions were given to guard against evaporation in the process of melting. Rain water and melted snow water were to be entered in separate columns in the record. The water equivalent of snow was recognized as being on the average 1/10, but the alternative of recording 1/10 of the average depth instead of melting was not authorized.[2]

The Signal Service and the Weather Bureau.—The earliest definite instructions upon the subject issued by the United States Signal Service are given in Instructions to Observer-Sergeants, dated September 30, 1873. These instructions provide that "Snow will be melted and then measured in the same manner as rainfall," evidently following the practice of the Smithsonian Institution, the then recognized authority on meteorological matters in the United States. A revision of the 1873 instructions as to snow measurements, made in 1875, repeated the original instructions with an added clause as follows:

Whenever from any cause snow can not be melted, the depth wil[l] be measured and 10 inches of snow recorded as 1 inch of rainfall.

This is the first occasion of the public recognition of the ratio 1/10 by authorities in the United States.

[1] Earlier but less extensive corps of observers were organized in 1817 by Josiah Meigs, Commissioner General Land Office, and in 1819 by the Surgeon General of the Army. See MONTHLY WEATHER REVIEW, February, 1909, 37: 87-89.—C. A., jr.

[2] Smithsonian miscellaneous collections, No. 19, p. 23.

In the 1881 edition of Instructions to Observers, the above specifications were repeated. In April, 1884, however, a very material amendment was promulgated as General Orders No. 40, April 11, 1884. This order directs the use of a snowgage and describes it (the gage described is practically the overflow of the present 8-inch standard raingage) and specifically directs the following be made of record:

(1) Time of beginning and ending of snow.

(2) Whether moist or dry.

(3) Amount of water collected in the snowgage from snow (or snow with rain).

(4) The same collected in the raingage.

(5) Depth of snow (before melting it) collected in the snow gage at each telegraphic observation.

The revision of 1887 includes the foregoing items but is silent as to the date upon which they became effective. Reference to the original order shows that it became effective July 1, 1884. No change was made in the next revision, which appeared in 1895 under the title "Instructions for Observers of the Weather Bureau", Washington, 1895. A short time previous to the last-named date, probably in 1894, Prof. C. F. Marvin, then in charge of the Instrument Division, published as Circular A, of that division, a pamphlet under the title "Instructions for Obtaining and Transcribing Records from Recording Instruments". In this publication, it was recognized that the ratio 1/10 was only roughly approximate and the observers were urged to determine the actual water equivalent of snow by either of two suggested methods. These instructions were later amplified somewhat and now appear in Circular E, Instrument Division, "Measurement of Precipitation"[3] and also in the pamphlet entitled "Instructions for Preparing Meteorological Forms", the latter first issued in 1905 and revised annually since that year. The 1916 edition contains directions for measuring snow under paragraph No. 110. The ratio 1/10 is still used when the observer is unable to melt the snow.

The water equivalent of fresh snow.

In the beginning of systematic snow measurements, observers were chiefly concerned with (1) the best means of catching the falling snow, and (2) its water equivalent, the latter in order that the record of precipitation might be complete. It was generally recognized that there were serious difficulties to be overcome in order to secure a true catch, and also that the snow varied considerably in density. The earliest discussions of the subject are largely concerned with questions of variations in density under different temperature conditions which attend the fall of snow (see for example, 1 in list of references).

A résumé of the official instructions as to the measurement of snow in England and other countries at that time (1872) will be found in Symons's "British Rainfall for 1872", pages 9-23. The rule in England as prescribed for observers of the British rainfall organization was either of the following: (1) Melt the snow caught in the gage by the addition of a previously ascertained quantity of warm water, then deduct this quantity and measure the residue as rain; (2) select a place where the snow has not drifted, invert the funnel (of the raingage) and, turning it around, lift and melt what is inclosed; (3) measure with a rule the average depth of snow, and

[3] Third edition, 1911 (W. B. No. 445).

take 1/12 as the equivalent of water. Observers were enjoined to try all these methods and to adopt that which they consider most trustworthy.

In subsequent issues of British Rainfall many interesting notes on the water equivalent of snow appear and it is pointed out that the ratio varies from 1/5 to 1/35.

Col. M. F. Ward, a member of the British Rainfall Organization, not only made many careful observations, but also contributed the results of his studies for publication in the annual volumes of British Rainfall. While Col. Ward's work was largely concerned with a determination of the catch of snow, yet it contains many valuable observations on snow density. A density as low as 0.026 was observed[4] by him in Canton Vaud, Switzerland, on January 16, 1880, and the remarkably low density of 0.008 was observed[5] in March, 1876. The maximum density observed was 0.221 and the mean density for different kinds of snow was [6]—

Minute crystals	0.075
Small snow	.100
Large dense flakes	.100
Large light flakes	.059
Round globules	.058

Lancaster (3) in 1888 published a summary of the existing data on snow density, based chiefly on a 20-year period of observations at the Alpine station of Grand Saint Bernard, altitude 2,478 meters, as follows:

	Mean density.
January	0.080
February	.080
March	.090
April	.110
May	.160
June	.180
July	.240
August	.180
September	.150
October	.150
November	.100
December	.080

Temperature-density relations.

Belgium.—Lancaster (3) points out that the greatest densities are observed in the summer months and the least in winter, and attempts to deduce a relation between the density of the snow and the air temperature at the time of its fall. He deduces from three years of observations, the following temperature-density relations:

Temperatures °F.:	Density
At 36	0.166
At 34	.143
At 32	.125
From 30 to 28	.111
At 27	.100
At 25	.090
From 23 to 19	.083
From 18 to 14	.077
From 12 to 5	.071

Germany.—Wengler (21) presents an abundance of good material respecting the density of freshly fallen snow in north Germany. Using the Potsdam observations,[7] he obtains the following temperature-density relations:

Temperatures °F:	Density.
From 5 to 14	0.046
From 14 to 23	.082
From 23 to 27	.086
From 27 to 30	.089
From 30 to 32	.103
From 32 to 34	.140
From 34 to 37	.235

Throughout the table of densities prepared by Wengler, and especially in the last-named group (34° to 37°F.), a number of cases of relatively high density appear. These, as explained by the author, were due to several causes, frequent among which was the tendency to increased density with temperatures above 32° and the fact that it was not always possible to exclude those cases in which the precipitation was partly in the form of sleet and rain mixed.

The same author using the records of snow measurements made at Potsdam during a period of 15 years, shows the error that is probable in assuming the ratio 1/10 to subsist at all times. His results are summarized in Table 1 below.

TABLE 1.—*Observed and computed water equivalents of snow at Potsdam.*

[Ratio 1/10 used in computed amounts.]

Month.	Precipitation as snow.		Differences.	
	Measured.	Computed.		
	Inches.	*Inches.*	*Inches.*	*Per cent.*
November	4.40	3.89	−0.51	−11.6
December	3.03	3.31	+.28	+9.2
January	8.31	9.06	+.75	+9.0
February	5.50	5.42	+.08	+1.4
March	4.85	3.82	−1.03	−21.2

The above results clearly show that for the beginning and the ending of the snow season the ratio 1/10 gives too low values and that during midwinter, as in December and January, the computed values are too high by about 9 per cent. The results for February closely approximate the truth, while in March the computed values are 21.2 per cent too low.

Wagon Wheel Gap, Colo.—An attempt to classify snow densities according to surface air temperatures as observed at the Wagon Wheel Gap Experiment Station[8] in Colorado, was not successful in establishing any definite relation between surface-air temperatures and the density of falling snow.

TABLE 2.—*Average snow densities at Wagon Wheel Gap, Colo., deduced from 6 years' observations and classified according to surface temperatures.*

Surface air temperature.	Cases.	Density.
°F.		
0 to 5	2	0.065
5 to 14	26	.097
15 to 24	57	.078
24 to 26	22	.076
27 to 30	32	.078
31 to 32	16	.085
32 to 34	11	.104
35 to 38	18	.096

Little importance is attached to this Table 2 since it is practically impossible to classify snowfall according to surface air temperature. The air temperature when snow begins to fall in the late Fall and early Winter, is of course relatively higher than in midwinter, and naturally as the fall of snow continues, the temperature falls.

Roughly speaking, snow may begin to fall at Wagon Wheel Gap at any surface temperature between 0° and 45°F. On January 4, 1913, set in a snowstorm lasting almost continuously for 30 hours. At the beginning,

[4] Symons's British Rainfall, 1879, p. 16.
[5] Symons's British Rainfall, 1875, p. 24.
[6] Symons's British Rainfall, 1874, p. 20.
[7] Ergebnisse der meteorologischen Beobachtungen in Potsdam im Jahre 1910, p. VIII.

[8] Maintained jointly by the Weather Bureau and the Forest Service of the Department of Agriculture.

the air temperature was 23°F. (5°C.) and falling very slowly. It reached 10°F (−12°C.) at 10 p. m. on that date; thereafter the fall was more rapid. reaching a minimum of −7°F. (−21.7°C.) at 8 a. m. the next morning. Snow continued falling until nearly 6 p. m. of the 5th. By that time, the temperature had risen from −7° to −3°F. The depth of the snowfall was 6 inches and the density 0.060. In general, the density is less in midwinter than in the transition seasons at the beginning and at the end of the cold season, respectively, as may be seen by the following table:

TABLE 3.—*Average density of fresh snow at Wagon Wheel Gap, Colo.*

Season.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.
1910-11	......	......	0.089	0.076	0.075	0.075	0.077	0.118	......
1911-12	......	0.084	.070	.083	.072	.079	.076	.073	0.150
1912-13	......	.082	.074	.055	.089	.081	.080	.108	.100
1913-14	0.100	.091	.085	.073	.064	.083	.086	.072	......
1914-15	......	.145	.200	.066	.072	.076	.076	.122	.144
1915-16	.100	.090	.088	.076	.089	.097	.091	.098	......
Mean	0.100	0.098	0.081	0.071	0.077	0.082	0.081	0.098	0.131
Inches of snow to =1 inch water	10	10	12	14	13	12	12	10	7.6

The observations at Wagon Wheel Gap, Colo., it should be remembered, were made at an altitude of slightly more than 9,500 feet where the precipitation of the cold season is wholly in the form of snow.

At the majority of observing stations east of the Rocky Mountains, the precipitation, especially at the more northern points, is frequently in the form of snow turning to rain or vice versa, and there is therefore by reason of the impossibility of separating the precipitation in the two forms, a lack of conclusive data on the subject.

Washington, D. C.—At Washington, D. C., latitude 38° 54′ N., in 10 years record, there were but 29 cases of snow not mixed with rain or sleet (ice grains), about three cases on an average per season.

The average density as determined from these observations is 0.098, the least was 0.026 on March 22, 1914; the greatest was 0.175 on March 3, 1916. The depth of snow on the latter date, however, was but 0.8 inch; but the surface air temperatures were under 32°, viz, 26° at the beginning and 24° at the ending of the snow.

Special attention is given by the Weather Bureau to the collection—through its network of cooperative stations, mountain snowfall stations, and by cooperation with the rangers of the Forest Service, especially in the far western States—of statistics of depth and density of the seasons' snowfall.

A monthly bulletin is distributed near the close of each month during winter through which persons interested in the probable water supply derived from melting snow may receive the latest available information thereon.

Colorado.—Section Director Frederick H. Brandenburg (22) of Colorado began the issue of monthly snow bulletins for that State as early as 1896, and other section directors began soon thereafter.

We have summarized from Director Brandenburg's reports for a single season the results shown in the small table below. At each of the stations in the State, the water equivalent of the snowfall was determined, usually by melting, and a record was also made of the depth. The last column contains the average density as determined from the average depth and the water equivalent of the snow. The latter is not shown.

TABLE 4.—*Average depth and density of snow in Colorado for a single season.*

Months.	Number of stations.	Average.	
		Depth.	Density.
		Inches.	
November	29	3.0	0.064
December	29	14.0	.062
January	44	16.0	.046
February	40	22.4	.069
March	46	14.5	.075

New York.—Measurements at Albany, N. Y., north latitude 42° 39′ for two winters (29 cases) give 0.110 as the mean density.

Five observations of the density of new snow (11) made at the same city by Mr. R. E. Horton in the winter of 1914, give 0.165 as the mean density.

Upsala, Sweden.—Westman and Jansson (9) made some very definite observations on the density and diminution in depth of a snow cover at the observatory at Upsala in 1902, and the density of fresh snow was carefully determined. The studies of these observers form one of the most thorough contributions to the subject that has yet appeared. We quote from their result the following table, transposing the values into English measures, for the benefit of any of our readers in the United States who may not be thoroughly conversant with metric measures and also in order to conform to the system of measures used throughout this paper.

TABLE 5.—*Westman's & Jansson's determinations of the density and temperature of snow at Upsala.*

Date.	Hour.	The snow layer.						Precipitation during preceding 24 hours.[a]	Remarks.		
		Depth.	Temperature.				Density.		Time.	Temperature of air.	
			Surface.		Bottom.						
1902		*Inches.*	°C.	°F.	°C.	°F.		*Inches.*		°C.	°F.
Feb. 10	2:45 p. m.	3.15	......	......	......	......	0.0384±0.0023	*0.03	6-1 p. m.	−12	10.4
Feb. 10	6:25 p. m.	3.31	−9.2	15.4	−5.4	22.3	.0476± .0025	(*)	6-6:30 p. m.	−12	10.4
Feb. 10	11:30 p. m.	3.50	−9.2	15.4	−6.2	20.8	.0600± .0010	(*)	8:30-Midnight	−11	12.2
Feb. 11	11:25 a. m.	5.47	−9.4	15.1	−5.2	22.6	0.0615±0.0009	(*) .19	6-11 a. m.	−12	10.4
Feb. 11	6:25 p. m.	5.12	−22.4	8.3	−7.0	19.4	.0630± .0009	......	......	......	......
Feb. 12	10:25 a. m.	4.49	−5.0	23.0	−3.5	25.7	0.0844±0.0009	(*) .04	5:30-7:45 a. m.	−4	24.8
Feb. 12	6:25 p. m.	4.17	−11.0	12.2	−4.6	23.7	.0921± .0009	......	......	......	......
Feb. 13	1:40 p. m.	3.70	−8.0	17.6	−4.2	24.4	.1111± .0018	.00	......	......	......
Feb. 14	10:30 a. m.	3.54	−11.2	11.8	−7.6	18.3	0.1121±0.0016	.00	......	......	......
Feb. 15	11:20 a. m.	3.39	−9.2	15.4	−8.4	16.9	.1210± .0009	.00	......	......	......
Feb. 16	1:00 p. m.	3.23	0.0	32.0	−1.2	29.8	.1403± .0021	.00	......	......	......

*Precipitation in form of snow.

[a] Measurements made at noon.

The authors remark on Table 5 as follows:

Variations in the specific density of a snow cover composed of recently fallen snow have been measured in only a small number of cases. Between February 10 and 12 a new layer of snow was formed while the temperature of the air was quite low and the wind velocity gentle. As this new layer was exceptionally porous and at the same time homogeneous, it was particularly favorable to a study of the variations of specific density. The snow was so soft (molle) that the cylinder above described could not be used to extract the samples, because the snow massed about the end of the cylinder without penetrating it when it was forced into the snow layer. Recourse was had to a plate of sheet iron 25 centimeters square, which was forced under the new snow at the surface of the old snow. In this manner a sample was cut in the form of a rectangular parallelopiped, having the plate as a base and the depth of the snow layer as its height. In this manner the compression of the snow was completely avoided. Having measured the dimensions and the weight of the parallelopiped, the specific density was calculated. Each of the values of specific density which appears in Table 5 is the mean of five different measurements. In that table, also, is indicated the probable error in the values of specific density and the depth and temperature of the new snow cover at the hour of observation.

It was established that there was a continual increase in the specific density, that for the most porous snow the increase was relatively rapid even though at the beginning the temperature of the air and that of the snow was not above 14° F. (−10° C.) and 15.8° F. (−9° C.). Finally, it appears that the density during the fall of snow varies between 0.0384 and 0.0844. Between the 12th and the 16th, after snow ceased falling, the increase in density continued, but was very irregular. On the average its value was 0.018 in 24 hours.

The very considerable temperature gradient in a layer of new snow is worthy of mention. It appears from Table 5 that there was on February 11 a maximum of 15.4°C for a depth of 13 centimeters, or 1.2 degrees for each centimeter, which proves that this snow was a very poor conductor of heat. For the density of the snow cover in question, 0.063, the coefficient of conduction is 0.00017°.[9] By comparison it may be noted that the value of this coefficient is for air 0.00005 and for ice 0.00568.

Density of old snow.

We now pass to a consideration of the density of a layer of snow that has been exposed to the weather for a greater or less time. Freshly fallen snow is composed of minute snow crystals intermixed with air. The quantity of air present is variable, depending on the size and structure of the crystals and, in a lesser degree, on the mechanical action of the wind. The longer snow is exposed to the weather the greater is the quantity of air which is expelled from it, and naturally the density increases. Moreover, as has been pointed out frequently by previous writers, snow that has been exposed for some time to the weather suffers a change in its internal structure, which tends to increase its density. The diminution in depth of a snow cover is generally due to several causes, acting singly or conjointly. Principal among these causes are: (1) An increase of air temperature, due to insolation or to the horizontal transport of warm air from other regions, sufficient to produce melting of the superficial layer of the snow cover; (2) the mechanical action of the wind, either in compressing the top layers or in breaking up the original snow crystals and distributing them in the form of drifts of finely pulverized snow; (3) by the evaporation and settling of the top layers, which doubtless, in the case of evaporation, must depend largely upon the climatic conditions of the region in which the snow layer may exist. The fall of rain, too, can have an important bearing on the structure of the snow cover, particularly if it is immediately followed by freezing weather. The well-known snow crust often owes its origin to this circumstance.

Intensive snow surveys in the United States.

So far as known, the first systematic measurements in the United States, of the density of the accumulated snow layer in spring were made by Mr. Charles A. Mixer (**12**), civil engineer, of Rumford Falls, Me., in the spring of 1903.

Mr. Robert E. Horton, hydraulic engineer, of Albany, N. Y., collected and published in 1905 the results of snow density measurements made in New York and New England (**10, 11**).

Within the last 10 years a number of intensive snow surveys at high altitudes, late in the spring, have been made under the direction of Weather Bureau officials, as noted in the following paragraphs. Previous work of a similar character was done by Prof. John E. Church, jr. (**24**), of the University of Nevada at Reno. In the spring of 1909 Church began a series of snow density determinations near Lake Tahoe, in the Sierra Nevada. Prof. Church has summarized the results of several thousand measurements on a series of blue-print sheets distributed in 1916. It is understood the results of his work will appear in the proceedings of the Second Pan American Scientific Congress (Washington, 1915–16), and also in a special bulletin of the Nevada Experiment Station.

Utah.—The pioneer of intensive snow surveying by the Weather Bureau is Mr. A. H. Thiessen, section director, Salt Lake City, Utah. Mr. Thiessen began with a survey of Maple Creek Canyon in the spring of 1911. The first survey covered 6,880 acres and 277 soundings for depth and density were made. The average depth was found to be 36 inches and the average density 0.320, or 32 per cent. This survey was repeated in the following year, and 297 soundings were made, or practically the same as before. These determinations gave, for the spring of 1912, an average depth of 42.5 inches and a density of but 0.240, or 24 per cent.

In 1914 the survey was made in the watershed of City Creek Canyon, from which a portion of the water supply of Salt Lake City is drawn. The results of that survey and also of the surveys in 1915 and 1916 are shown in Table 6.

TABLE 6.—*Snow densities in City Creek Canyon, Utah, 1914–1916.*

Years.	Subdivisions.								Whole area.
	A	B	C	D	E	F	G	H	
1914	0.34	0.33	0.35	......	......	0.34	0.34	0.36	0.34
1915	.32	.30	.31	0.32	0.30	.31	.32	.33	.31
1916	.36	.32	.35	.36	.33	.32	.34	.33	.34

Idaho.—Edward L. Wells, section director at Boise, made some density measurements in the neighborhood of Silver City in February, 1914. He found an average depth of 33.1 inches and a density of 0.290. In the neighborhood of Sheep Hill the depth in the same month was 27.0 inches and density 0.290.

An intensive survey was conducted under the same official in the watershed of Cottonwood Creek in 1914, 1915, and 1916. The depths and densities are given in Table 7. (See also this REVIEW, 1914, **42**: 634; 1915, **43**: 567.)

TABLE 7.—*Average depths and densities of snow in the basin of Cottonwood Creek, Idaho.*

Years.	Below 4,000 feet.		Between 4,000 and 5,000 feet.		Between 5,000 and 6,000 feet.		Above 6,000 feet.	
	Average depth.	Average density.	Average depth.	Average density.	Average depth.	Average density.	Average depth.	Average density.
	Inches.		*Inches.*		*Inches.*		*Inches.*	
1914	4.3	0.30	29.8	0.33	41.3	0.35	72.6	0.35
1915	4.0	.30	19.4	.32	26.3	.30	36.8	.30
1916	36.5	.34	46.1	.35	56.8	.37	121.0	.36

[9] *Jensson, M.* Ueber die Wärmeleitungsfähigkeit des Schnees. Ofvers., Kongl. Vet. Akad. Forh., Stockholm, 1901.

Arizona.—Depth and density measurements were made in the latter part of March, 1914, 1915, and 1916 in the Paradise Creek Valley region, Apache County, Ariz., approximately in latitude 34° N., longitude 109° 45′ W. Paradise Creek is a tributary of the White River, which latter has its source in the high mountains in the southwestern part of Apache County. The measurements of 1914 are presented in Table 8, in which the arrangement is according to altitude.

TABLE 8.—*Average snow depths and densities, Paradise Creek valley, Ari.*

Number of measurements.	Elevation.	Average depth.	Average density.
	Feet.	*Inches.*	
88	8,250 to 8,750	13.5	0.346
133	8,750 to 9,250	20.0	.319
266	9,250 to 9,750	27.6	.333
15	10,000	49.0	.305

The greatest depths were found on the north and northeast slopes. The density did not vary materially with slope. The greatest density, 0.400, was found in a layer 8 inches thick in the aspen forest. Low average densities were found in layers having a total depth of 15, 19, 30, and 50 inches, respectively. There does not appear to be an increase in density with increase in depth.

The determinations in 1914 and 1916 were made by Observer Kenneth Meaker; in 1915 by Observer B. L. Laskowski. The measurements in 1915 and 1916 were greately hindered by untoward weather conditions, it being physically impossible to prosecute the work to a successful conclusion; nevertheless, 61 determinations of depth and density were made in 1915 at altitudes ranging from 7,875 to 8,500 feet and depths were encountered ranging from 18 to 47 inches. The average depth as determined by 61 measurements was 36 inches and the average desity 0.251. Densities as great as 0.346 and as small as 0.167 were encountered. The high densities were found in a snow layer having an average depth of 32 inches. The low values were found in a layer of but 15 inches in depth.

The weather conditions in 1916 were even worse than in the preceding year and but 32 measurements were obtained. A driving wet snow had prevailed for 36 hours, and this was followed by a heavy rain, thus making roads and trails impassable. When the rain ceased the weather turned cold and on the top of the water-soaked snow formed a crust that was not strong enough to bear a horse, and hence a camp outfit could not be taken into the snow fields.

The average depth of the snow cover where measurements were practicable was 18.2 inches; its average density was 0.600. In some cases the snow layer was practically a mass of slush, having a density of 0.900. The lowest density recorded was 0.410. Flood conditions prevailed on all the streams of the region and the flood flow passed over the spillway of the Roosevelt Reservoir, the latter being full at the time.

Wyoming.—The Rock Creek Conservation Co. of Rock River, Wyo., in cooperation with the U. S. Weather Bureau, made a survey of the extent, depth, and density of the snow cover in Sand Lake, Wyo., drainage. The geographical coordinates of Sand Lake, Wyo., are approximately lat. 41° 25′ N., long. 106° 12′ W. The Medicine Bow Mountains are immediately to the westward of Sand Lake, although the lake itself is at an altitude of 10,120 feet above mean sealevel, and portions of the drainage area rise to 10,700 feet. The total area surveyed was 1,774 acres and 64 determinations of depth and density were made. The average depths and densities, classified by elevation, appear in Table 9.

TABLE 9.—*Snow depths and densities in the Sand Lake, Wyo., basin, 1915.*

Number of measurements.	Elevation.	Average depth.	Average density.
	Feet.	*Inches.*	
* 4	10,120	42.75	0.270
10	10,120-10,200	55.20	.237
7	10,200-10,300	60.29	.251
20	10,300-10,400	61.30	.261
5	10,400-10,500	60.60	.260
16	10,500-10,600	60.31	.252
2	10,600-10,700	75.00	.257

* On Sand Lake.

A classification according to slope, or the direction in which the various parts of the drainage face, gives the following results in Table 10:

TABLE 10.—*Snow depths and densities at Sand Lake, Wyo., classified according to slope.*

Slope.	Depth.	Density.
	Inches.	
Northward	64	0.250
Northeastward	62	.270
Eastward	59	.250
Southeastward	55	.270
Southward	52	.230
Westward *	* 35	.090
Northwestward	61	.250
Lake surface	45	0.270

* Based on a single measurement.

A classification according to surface cover gives the following:

	Av. depth.	Density.
In open parks	58 in.	0.259
In timber	61 in.	0.246

The total water content being practically the same in both cases. The results of this survey do not show a uniform increase in density with increase in depth of the total snow layer. The snow cover on the lake, although of less depth than elsewhere, was of greater density.

Nevada.—An intensive snow survey in the Carson and Walker Basin in this State was made in 1914 under the direction of Observer H. S. Cole. The results of this survey are yet in manuscript. In 1916, a series of density measurements were made from Reno as a base station, in cooperation with the University of Nevada. See H. F. Alciatore, (23).

THE DENSITY OF NEW SNOW AND OLD GLACIAL SNOW.

One of the most illuminating discussions of snow density available from European sources is that of Dr. Alfred Defant (25) of the Austrian Meteorological Institute, who spent a vacation in August, 1908, on the summit of the Sonnblick, 3,095 meters (10,154 feet), making determinations of the density of the snow on Goldberg Glacier.

After describing the apparatus used and the place and manner of the determinations, he says, in part, speaking of a series of density determinations with depth made at two places:

In both series an increase in density with increase in depth is observed and certainly in both cases the density increases to a maximum at a depth of 87.5 cm. (34.5 inces). Then the density decreases a little and is followed by a second increase. Figures 2 and 3 give a graphic representation of these mean values. [Fig. 2 of Defant here given as fig. 1].

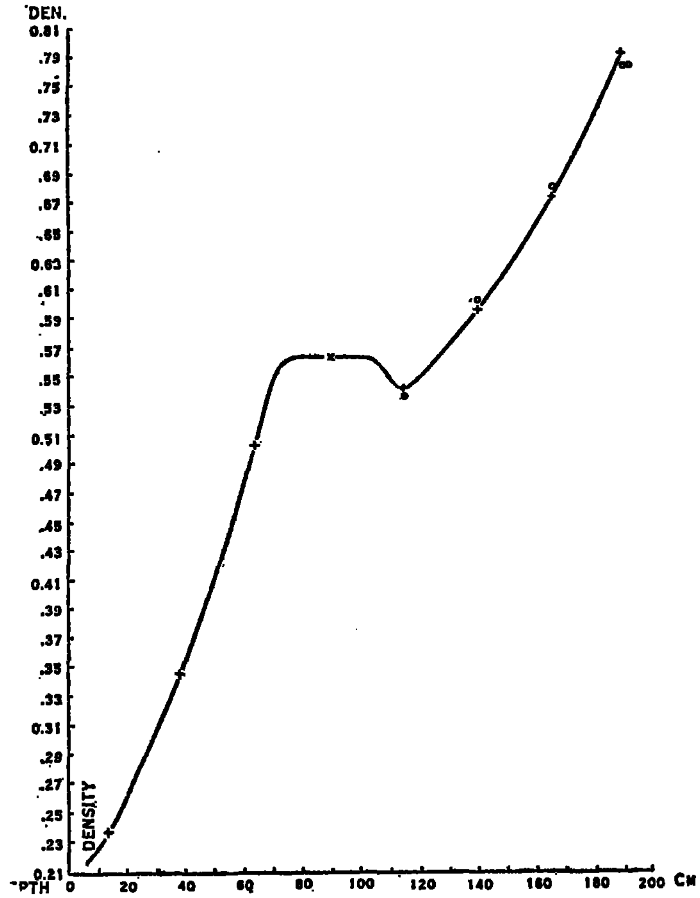

FIG. 1.—Defant's figure 2 showing his curve of relation between depth and density of snow.

In the first series, according to the figure, the maximum density is reached at a depth of 82 cm. (32.3 inches); in the second, at a depth of 70 cm. (27.6 inches). The cause of these mean densities lays in the weather conditions before the measurements were begun. Moderately heavy rains had barely saturated the top layers when they were frozen, forming an ice crust which at most had a thickness of 10 cm. (3.9 inches), hence the rainfall did not soak deeply into the snow. After a somewhat warmer period there followed colder weather and upon the ice crust thus formed there was deposited the fall of an extensive snowstorm, which buried the crust to a considerable depth, separating the old snow from the new. One clearly perceives the difference between the two snow layers. The upper snow layer consisted of light, dazzling upper snow (Hochschnee), which is composed of very small ice crystals, thus forming a mixture of ice and air.

Under the ice crust, on the other hand, the structure of the snow was coarser. The snow was heavier, granulated, and no longer dazzling white, as on the upper layer. We have here pure glacial snow. The size of the grains increased with the depth and, strictly considered, one recognizes that they consist of transparent ice in which many very small air bubbles are inclosed. The top snow has completely lost its crystalline structure, since through frequent thawing the points and needles of the crystals are melted off and the penetrating snow-water collects later about single kernels of ice and is frozen together in larger grains. Measurements enable us to distinguish readily between the fine-grained old snow in the upper layers under the ice crust and the coarse-grained old snow at depths of say about 3 meters. * * *

The increase in density with depth is due to a variety of causes. Freshly fallen snow diminishes in volume when the temperature becomes higher. Snow is made up of an extensive net of capillary tubes, which take up water as a sponge. The air, of which the greater part of a definite volume of snow is constituted, is expelled through the tubes and the density of the snow increases. In the exchange of heat in the surface layers of the snow stratum it is first of all to be considered that the heat is completely used in melting the upper layers and only indirectly exercises an influence upon the lower layers; that the snow-water slowly soaks or filters into the lower layers. On the contrary during the prevalence of cold, when it continues for a time, it gradually penetrates deeper and deeper into the layers, until finally it penetrates the deepest and not as the heat which is fully consumed on the surface.

Another cause of the increasing density of the snow with depth is the pressure which in the upper snow layers exercise upon the lower. The volume of the snow becomes the smaller, the greater is the pressure which weighs upon them. The air is squeezed out and the density *increases*. * * *

In the analytical presentation of the subject of snow density as dependent upon depth, most authors nearly always assume that the density increases proportionately to the depth and that when $\rho=$ the density of the snow, $z=$the depth counting from the snow surface, then the increase in density will be represented by the formula

$$\rho=\rho_0+az.$$

An inspection of our graphic presentation [fig. 1] shows directly that this relation is not fulfilled, surely for the upper layers. The increase follows a curve slightly concave to the axis of ordinates and can not therefore be represented by a linear relation.

A logarithmic relation, first derived by Abe [10] gives values, as we shall see, which better agree with the actual observed values. If we designate by p the pressure of the snow cover in the depth z, then

$$\rho dz=dp.$$

Assume further that the density of the snow is proportional to the pressure of the overlying stratum of snow, then

$$\rho=\rho_0+kp,$$

where ρ_0 is the density at the surface and k is a constant. From these two equations for ρ we can eliminate p and we then have

$$kdz=\frac{d\rho}{\rho}.$$

If ρ_0 is the density at the surface it follows that

$$\log \rho=\log \rho_0+kz.$$

These relations were employed in the four branches of our curve [fig. 1], and gave for the increase of the density with depth the following:

For [fig. 1] applicable from $z=0$ to $z=80$

$$\log \rho=\log 0.2404+0.00529\ z$$

For [fig. 1] applicable from $z=162.5$ to $z=312.5$

$$\log \rho=\log 0.4863+0.00025\ z$$

For figure 3 [not reproduced] applicable for values of z between 0 and 70,

$$\log \rho=\log 0.3198+0.00201\ z.$$

These four equations represent the branches of the curves with great precision; indeed, the departures of observed and computed values are well within the error of observation.

THE DIMINUTION OF A SNOW COVER.

It is well known that a snow layer, especially if composed of freshly fallen snow, diminishes in depth rapidly at first, then at a much slower rate. The amount of shrinking in 24 hours varies, of course, in accordance with the prevailing atmospheric conditions. A high wind, for example, will not only drift freshly fallen snow, but will compress the superficial layer even where there is no drifting. Many examples of the compression or packing of snow by high winds were observed by the writer at Mount Weather, Va., during the winters of 1909–10, 1910–11, and 1911–12, but no quantitive values as to the amount of the compression were secured. The snowfall observer at Government Camp, Oreg., in the Cascade Mountains, reports a shrinkage of 16 inches in 24 hours on January 15, 1916, with a high wind and a daily mean temperature of 9°F. This value is, of course, exceptional, but many well-attested cases are at hand wherein the shrinkage was from 4 to 6 inches. At the height of the melting season the disappearance of snow by melting sometimes reaches the high value of about 8 inches daily (**26**).

[10] Meteorol. Ztschr., 1908, 25, 461.

Dr. J. Westmann (8) briefly discusses the shrinkage of a snow cover at several points on the public square in Upsala, separated from each other by short distance. He selected a place where the snow cover was fairly uniform and had a depth of approximately 20 cm. (7.8 inches). Ten measurements were made at points distant from each other about 3 meters (9.8 feet) and the mean of these 10 measurements was adopted as the mean depth for the time and place. Continuing these measurements over a period of 12 days in March, 1901, during which time thawing weather did not prevail, he was able to accurately note the diminution of the snow cover day by day. Another series of measurements was made in snow that had been shoveled together in which the total depth was at one time 54 cm. (21.2 inches). The average temperature during the period was 31.1 °F. The diminution in depth of the snow cover was greatest in the snow that had been piled together artificially, the maximum decrease recorded in 24 hours being 4.8 cm. (1.9 inches). Where the snow lay as it fell, the maximum decrease recorded in 24 hours was 3.93 cm. (1.53) the average daily decrease being 1.28 cm. (0.5 inch).

Dr. Westmann considers the loss due to evaporation as being of small importance and points out that in some cases the gain by condensation more than balances the loss by evaporation.

The water content of the snow was determined by weighing a known volume taken from the same points at which depth measurements were made. Two series of density determinations were made, the first for a top layer of 12 cm. (4.7 inches) and the other for a layer of 6 cm. (2.4 inches) next to the earth's surface. The results show, as was to be expected, that the density increases with the depth.

Dr. Westmann also points out that the water equivalent of the snow cover, which was 70 mm. on March 10, had diminished to 30 mm. on March 23. He considers the loss of 40 mm. to have been due to melting snow, the greater portion of which flowed away. During the melting the structure of the snow changes essentially, the ordinary snow becomes changed into angular grains, when the adhesion between these grains becomes small through intense melting, the structure of the snow becomes as coarse sand.

The same author in collaboration with M. Jansson discusses at length and in great detail the several influences contributing to a diminution in depth of a snow layer. (See p. 105.)

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GROWTH, SETTLING, AND FINAL DISAPPEARANCE OF A SNOW COVER IN THE SIERRA NEVADA, 1915–16.

By HENRY F. ALCIATORE, Meteorologist.

[Dated: Weather Bureau, Reno, Nev.—,1917.]

The following is a brief account of the controlling factors which determined the growth, settling, melting, and final disappearance of the snow cover of the 1915–16 season at four typical Weather Bureau mountain snowfall stations in the Lake Tahoe watershed. The stations selected were: Tahoe and Tallac, Cal., on the west side, and Marlette Lake, Nev., and Bijou, Cal., on the east side of the lake. All of these, except Marlette Lake, are on the shores of Lake Tahoe. Marlette Lake is a small body of water about 1,700 feet above the surface of Lake Tahoe, 2 miles east of the latter.

The season opened with a general snowstorm, November 8, 1915. November, January, and May were colder than usual, but February, March, and April were quite mild, particularly February. If in the absence of humidity, wind, and sunshine data for the places named, we consult the records of the nearest Weather Bureau observatory, namely, those of Reno, Nev., we find that from March to June the weather was unusually dry and windy and the amount of insolation considerably above the normal for the season, yet, in spite of these conditions, the snow cover finally disappeared at about the usual time of year at Marlette Lake, and somewhat ahead of time at the other stations.

Speaking generally, if we exclude impurities, a snow cover consists of two elements, and only two, i. e., snow and air. As a rule, fresh snow contains more air than snow, and the reverse of this holds true for the lower layers of a snow cover. For example, at one point in the Carson watershed, the snow was 10 feet deep, and its average density was 40 per cent; hence a cylinder of that snow, of one square foot base, would have contained about 6 cubic feet of air, and only 4 cubic feet of snow.

The details of the topography, geographical location, etc., of each station whose records have been used in this paper will be found in Table 11. The first three are on the lake shore, while the fourth, Marlette Lake, is 1,670 feet above the lake surface, and about 2 miles inland, on the eastern part of the drainage basin of the lake.

TABLE 11.—*Location of mountain snowfall stations.*

	Altitude.	Latitude. (N.)	Longitude. (W.)
	Feet.	° ′	° ′
Tahoe, Cal.	6,230	39 9	120 12
Tallac, Cal.	6,230	38 56	120 2
Bijou, Cal.	6,230	38 57	119 58
Marlette Lake, Nev.	7,900	39 10	119 55

As pointed out by Prof. Henry for the high Sierras of central California (27), so in the Tahoe Basin the fact that a considerable portion of the snow on the ground in midwinter settled or packed through natural causes aside from the occurrence of warm weather attended by rain is evident. In fact, the greatest amount of fortnightly settling at any station, namely, at the rate of 7.2 inches per day (Marlette Lake) occurred in January, the coldest month of the season, and one of the coldest on record. The average daily settling of the snow cover for the entire season, in inches, was 2.2 inches at Tahoe, 1.6 at Tallac, 1.5 at Bijou, and 1.7 at Marlette Lake. Comparing these values with the corresponding ones given by Henry for Fordyce Dam, Summit, and Tamarack, Cal., for a period of years, which were 1.9, 2, and 2 inches, respectively, we note that Tahoe, Cal., at an altitude of 6,230 feet, shows a slightly greater rate (in 1915–16) than the average rate given for Tamarack. The most pronounced settling occurred at all stations in the Tahoe Basin in January, the month of heaviest snow; at Tallac, in February, a month of scant snowfall.

Table 11 below has been prepared to show the daily changes in depth of snow cover at a single station in the Tahoe Basin for the period November 9 to December 31, 1915. The amount of snow, as it fell day by day, has been entered in the second column and the total depth of the snow cover on the ground is given in the third column each day. It will be readily seen that the